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Report Title

Conveyor Belt Transport; the Role of Friction and Mass in the Separation of Arbitrary Collections of Microparticles

ABSTRACT

We have investigated the role of interfacial chemistry, friction, and mass on the behavior of collections of microparticles and nanoparticles. These objects are the potential building blocks of any number of nanoscale and microscale devices and machines. To create such devices, a "nano-factory" is required, where creative combinations of "top-down" and "bottom-up" approaches are integrated to create a versatile and reliable factory. A key component of such a factory is a conveyor belt system for mechanically transporting, separating by mass and chemical species, and aligning nanoparticles in controlled ways. The conveyor belt needs to be chemically versatile, and hence organic/polymeric in nature. The nature of inertial motion is intimately connected to the interface between the particle and substrate on which it lies. A key to understanding the influence of this complex interface is to systematically vary the contact between components and observe the changes in behavior. We have gained an understanding of the role of interfacial chemistry, friction, and particle mass in this dynamic system.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Microparticle manipulation using inertial forces
M. Eglin, M.A. Eriksson, and R.W. Carpick, Appl. Phys. Lett., 88 091913/1-3 (2006).

Lateral force calibration in atomic force microscopy: A new lateral force calibration method and general guidelines for optimization
R.J. Cannara, M. Eglin, R.W. Carpick, Rev. Sci. Instrum., 77 (5), 53701/1-11 (2006).

Invited Review Article: Polydiacetylene films: A review of recent investigations into chromogenic transitions and nanomechanical properties
R.W. Carpick, D.Y. Sasaki, M.S. Marcus, M. A. Eriksson, and A.R. Burns. J. Phys.: Cond. Matt., 16,(23), R679 -R697 (2004).

Number of Papers published in peer-reviewed journals: 3.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Invited Technical Magazine Article: Measurements of in-plane materials properties with SPM
R.W. Carpick, M.A. Eriksson, MRS Bulletin, 29 (7), 472 (2004).

Number of Papers published in non peer-reviewed journals: 1.00

(c) Presentations

Microparticle Manipulation Using Inertial Forces
Michael Eglin, Mark A. Eriksson, and Robert W. Carpick
American Physical Society March Meeting, Los Angeles CA, March 2005.

Microparticle Manipulation Using Inertial Forces
Michael Eglin, Mark A. Eriksson, and Robert W. Carpick
Materials Research Society Spring Meeting, San Fransico, CA, March 2005.

Invited talk: The response of monolayers and organic networks to stress as a function of molecular architecture: Applications in nanoscale tribology and patterning
R.W. Carpick
Materials Research Society Fall Meeting, Boston, MA, November 2005.

Number of Presentations: 3.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED	
Michael Eglin	1.00	No
Nicklaus Smith	1.00	No
FTE Equivalent:	**2.00**	
Total Number:	**2**	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Robert W. Carpick	0.08	No
FTE Equivalent:	**0.08**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	
Christopher Torres	0.25	No
Tim Swenson	0.25	No
FTE Equivalent:	**0.50**	
Total Number:	**2**	

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

List of Illustrations:

1. Statement of Problem Studied:

Objective: Our objective is to understand the behavior of collections of particles while experiencing inertial motion. A substrate coupled to a shear-polarized piezoelectric actuator is used to induce inertial motion. Small particles are deposited onto the substrates, and mechanical actuation through piezoelectrically-induced inertial motion is used to manipulate the particles (Fig. 1). Ultimately, the interface between particle and substrate plays an important role in motion behavior due to the frictional component. We have varied the nature of this interface using silane chemistry, which will serve as a method for systematically studying and understanding the contribution of friction towards global motion behavior.

Impact: The controlled manipulation of small particles by mechanical means is fundamentally interesting from a scientific viewpoint. It combines the topics of nano-scale surface/interface structure, chemistry, and tribology (the study of friction, adhesion, lubrication, and wear) with the study of mechanical excitation at the micro/nano-scale. Application areas include the dynamic organization, transport, separation, and alignment of particles, surface cleaning methods for a wide range of device technologies, and micro/nanosystem design strategies. While a substantial body of work exists on the study of flow and organization in colloidal suspensions, the study of particle motion and interaction on dry surfaces appears to be almost completely unexplored.

2. Summary of Most Important Results

The highlights of our accomplishments in this reporting period are listed here and described in more detail further below:

a) Using a tailored parabolic waveform, succeeded in transporting particles and studying the behavior as a function of drive amplitude.
b) Implemented the use of humidity-control chambers in which the shear piezo can be actuated and the particle motion observed and recorded using optical microscopy. Observed that varying the humidity significantly affects the particle motion; in particular, silica particles can be transported more uniformly and at much lower forces under dry conditions for identical interfaces.
c) Demonstrated that particle motion depends on the nature of the interface between particle and substrate.
d) Discovered that aggregates of particles exhibit motion consistent with single particles of higher mass.

These are described in more detail below.

2a. Drive amplitude

With the drive signal *U(t)* chosen to be a repeated parabolic signal inset), we calculate the surface displacement *x(t)* using Newton's equation of motion as the following:

$$x(t) = d_{15} \cdot U(t) = d_{15}\left(8 \cdot U_m \cdot f_d^2 \cdot t^2 - U_m\right) \quad (1)$$

for $t \in \left[\frac{-1}{2f_d}, \frac{1}{2f_d}\right]$, and its periodic continuation outside this interval. d_{15} is the piezoelectric coefficient, f_d the drive frequency, and U_m the drive amplitude. During the smooth parabolic part of the displacement (figure 2), the particles move laterally with the substrate at a constant, low acceleration (because the second derivative of the parabolic displacement in equation (1), *i.e.* acceleration, is a constant). At the cusp of the waveform, the direction of the surface displacement is suddenly reversed and the particles, due to their inertia, continue sliding a small distance.

As expressed in the most recent Interim Progress Report, the motion behavior of particles contained within a device described here is proportional to the drive frequency. Additionally, the motion behavior can be altered by systematically changing the drive *amplitude*. Figure 3 illustrates the effect of changing amplitude has on different particles. 200 micron particles do not exhibit much change as a function of drive amplitude, while 90 micron particles display a nearly linear response to drive amplitude. This is likely explained by the fact that the larger mass associated with the 200 micron particles (about 11 times as massive) is less sensitive to changes in drive amplitude within the region explored.

2b. Dependence on humidity

Observed particle motion can also be influenced by environmental conditions. Using a chamber to control these conditions, it can be observed that a reduction in humidity will result in greater "performance" of the device, i.e. more particles will move under conditions that are identical save the relative humidity. Figure 4 illustrates the motion behavior as a function of relative humidity. It is hypothesized that lowering the relative humidity will decrease the physical size of the water meniscus inherent on hydrophilic surfaces such as silica. The images shown in figure 4 illustrate this effect quantitatively.

2c. Interfacial influence on motion behavior

The motion behavior is strongly affected by the nature of the interface between particle and substrate. There are many factors governing this interaction, such as quality of material, ambient conditions and contact area. By modifying the chemical nature of substrate, particle or both, the motion behavior will change accordingly. Using silane chemistry, silica surfaces are easily modified to be either very hydrophobic (using long-chained silanes, such as octadecyl trichlorosilane) or hydrophilic by cleaning in an

oxidizing solvent (such as piranha). This yields four interfacial conditions: a hydrophilic substrate and particle, a hydrophobic substrate and particle, and a mix of surface chemistry with one component being hydrophobic and one being hydrophilic. Figure 5a illustrates the motion behavior of 200 micron spheres under two different interface conditions, and figure 5b represents the behavior of 90 micron spheres under these same conditions. Surprisingly, the lower friction interfaces yielded poorer motion statistics than did the higher friction interfaces for comparable drivewaves. Consulting figure 2, it is expected that inertia will build up during the "slow" portion of the wave, and this inertia will carry the particle some distance proportional to that inertia when the substrate changes direction at the waveform cusp. The result of the lower-friction interfaces yielding poorer motion statistics suggests that there is some sliding occurring during the "slow" portion of the parabolic drive wave. As a result of the motion behavior as a function of interface, a comparison of motion behavior using drivewaves that had identical "velocities" was conducted. By increasing the amplitude and decreasing the frequency proportionally, the "slow" portion of the drive wave becomes even slower, but the "fast" portion remains as fast. Implementing this systematic variation showed that the poorest motion was observed for the interfaces containing uncoated particles. More interestingly, it was observed that aggregates of particles appeared to have a larger impact on motion behavior.

2d. Aggregate motion

It was observed that the motion statistics depended on the global concentration of particles in addition to the interfaces with differing friction. Collecting global motion statistics yielded results indicating that the lower friction interfaces showed poorer motion behavior overall. Within these global measurements, it was observed that the number of aggregates also had a significant effect on the motion statistics. As the number of aggregates increased, the overall motion statistics increased. As aggregates of particles form, the mass of this unit of material increases monotonically. The contact area also increases by the same proportion, suggesting that there should be no global change in motion. The observed behavior shows that as the aggregate size increases, the motion statistics increase as well. With an increase in friction, it is assumed that these groups of particles are more likely to stick (as opposed to sliding) during the inertia-gathering portion of the drivewave, and therefore more likely to experience motion. Figure 6 illustrates these results. When tabulating groups of particles together as n-mers of identical sizes, it can be seen that as the n-mer increases in size, the normalized fraction that move increases accordingly.

Summary

We have demonstrated a way to induce motion of large numbers of microparticles on a surface with no carrier medium. The method is simple and versatile, with the only prerequisite that the combination of particle mass and substrate acceleration must produce enough inertia to overcome the friction force of the particle/substrate interface. Humidity has a significant affect on motion behavior, likely due to the formation of a meniscus on hydrophilic particles. By varying the surface chemistry of the substrate and particle, the motion behavior can be altered accordingly. It is observed that the lower

friction interfaces generally show fewer tendencies towards good motion of particles, believed to be due to a slipping of particles during the “slow” portion of the drivewave. Aggregates of particles generally move better than single particles. It is believed that this is due to the increase in mass (resulting in more inertia) *and* an increase in friction (resulting in less opportunity for sliding in the “slow” region of the drivewave).

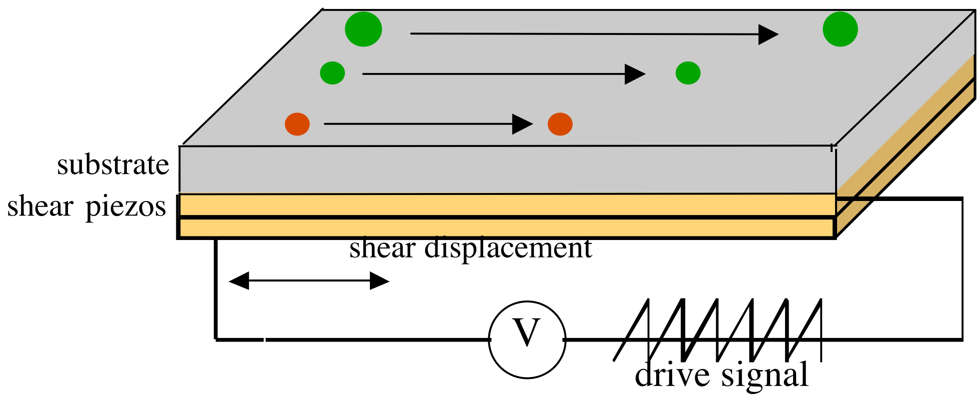


Fig. 1. Schematic of the conveyor belt concept. When actuated, particles move linearly along the preferred direction. Motion will be mass and species dependent as determined by mechanics and interfacial chemistry respectively.

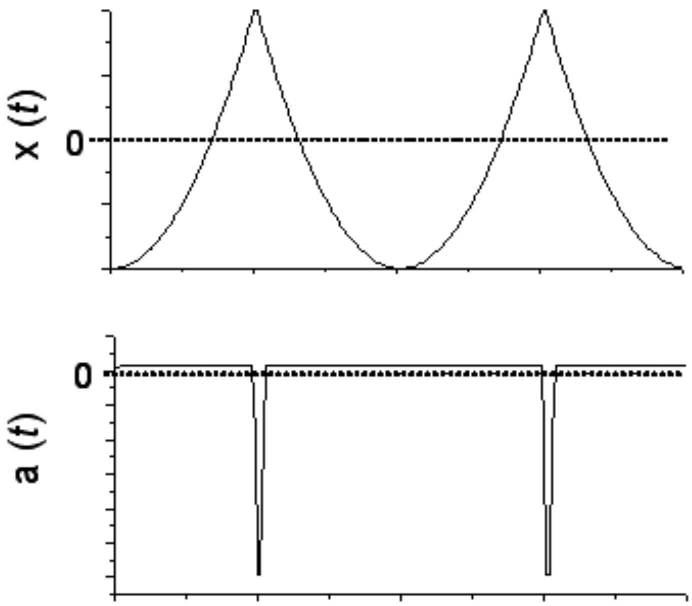
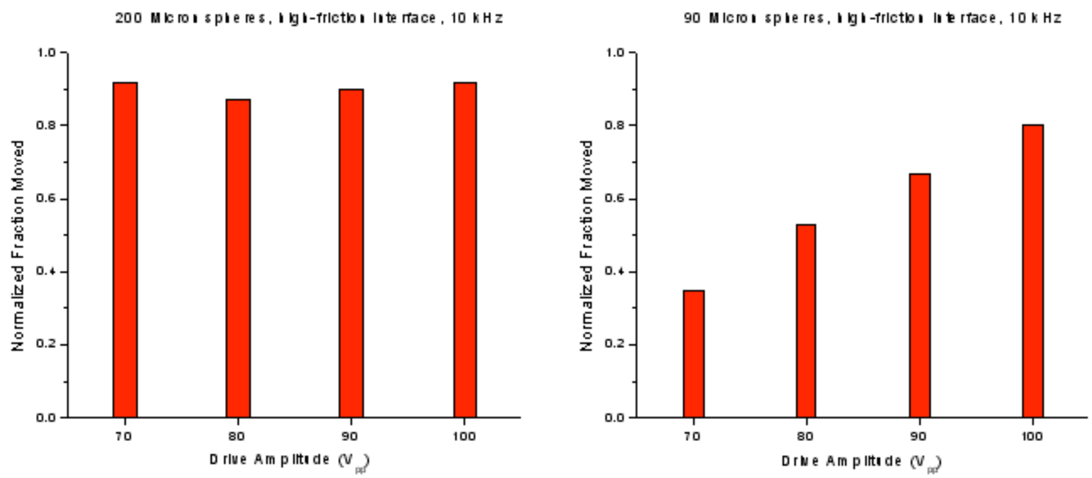
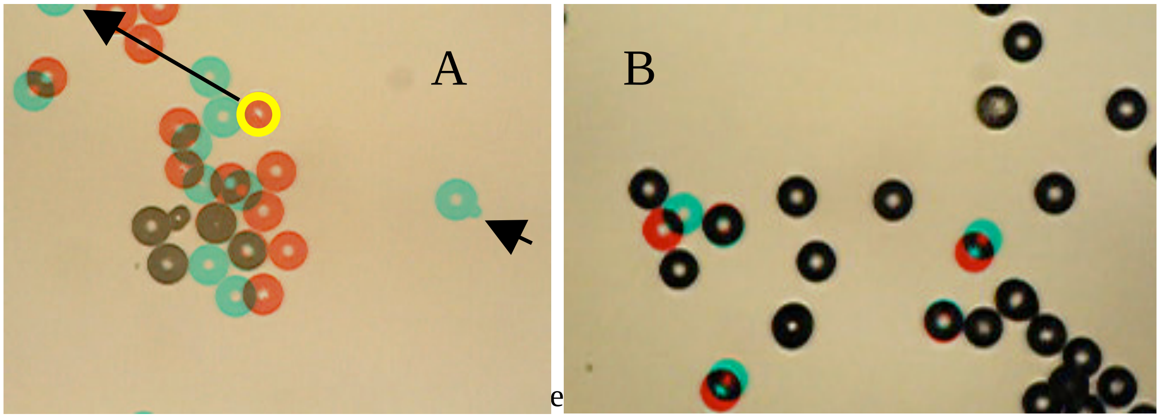


Fig 2. “Slow” vs. “fast” portions of the drivewave. Viewing the acceleration plot (second derivative of the displacement plot) it can be seen that there is a slow positive acceleration, followed by a fast negative acceleration which corresponds to the peaks of the parabola. It is during this slow portion of the drivewave that the inertia required to induce motion is generated. The fast portion of the drivewave accelerates the surface in the opposite direction, allowing the particle to break free of the static friction holding it in place during the slow portion of the drivewave.



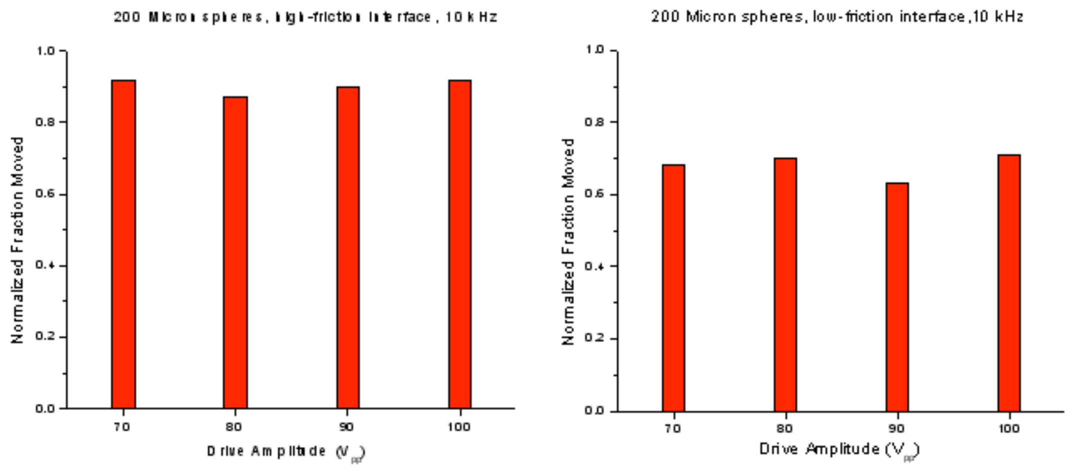
capturing movies during actuation. The number of particles moved divided by the total number of particles determined the normalized fraction of motion. These plots illustrate the role of mass in the described mechanism. The 200 micron spheres (left) do not show a trend in motion behavior as a function of drive amplitude, while the 90 micron spheres show a nearly linear dependence under the same set of conditions.



e

(RH<7%). (b) 200 micron glass spheres in ambient conditions (RH ~ 65%). These images are views as stacks of images taken from a movie which was used to record motion. The first and last frames are superimposed. When a particle is stationary throughout the application of the drivewave, it appears black. When motion occurs, this registers as two spots of different colors (red and blue, where red represents the initial position of the particle, and blue represents the end position of the particle). About 75% of the particles actuated at low humidity moved (12 of 16), while only 17% of the particles moved in ambient conditions (3 of 23). The difference in contrast is due to the fact that the particles on the left are enclosed within an environmental chamber.

A



B

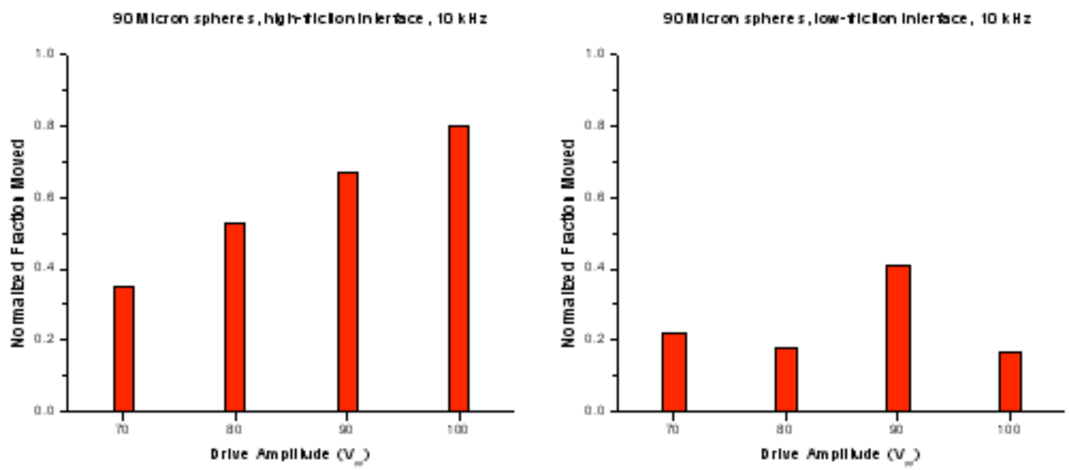


Fig. 5. (a) 200 micron glass spheres enclosed within an environmental chamber (RH<7%) as high- and low-friction interfaces (left and right, respectively). (b) (a) 90 micron glass spheres enclosed within an environmental chamber (RH<7%) as high- and low-friction interfaces (left and right, respectively). There is still little change in the motion behavior of the 200 micron spheres as a function of drivewave, but there is overall a decrease in the motion behavior between the high- and low-friction interfaces. This trend is mirrored with the 90 micron spheres.

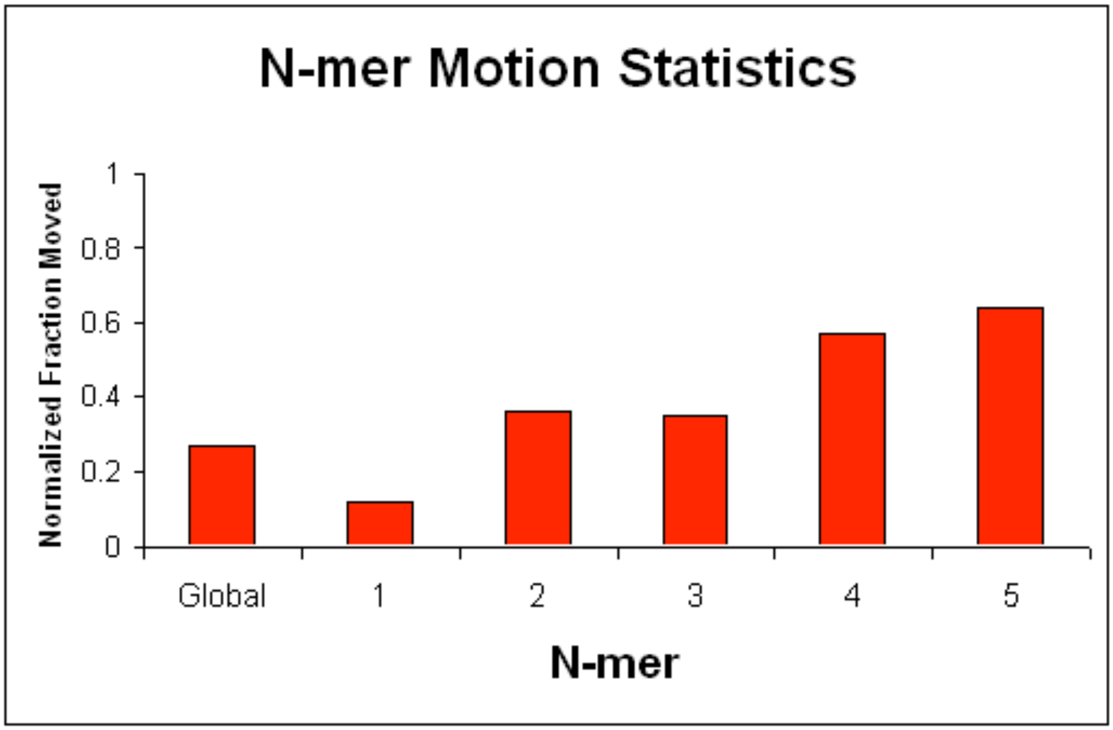


Fig.6. N-mer motion statistics. Represented here is the fraction of entities that moved during a period of actuation. The global number is the absolute particle motion. The numbered columns represent the number of particles associated with each aggregate (i.e. 1 represents a monomer, 2 represents a dimer, etc.). Globally, about 27% of the particles moved when tabulated individually. It is clear that monomers show the least amount of motion, while pentamers show the greatest. (it is worth noting that pentamers are not very common, and are typically observed only when there are large concentrations of particles on the substrate).